(12)

A Conceptual Model for Predicting Pilot Group G Tolerance for Tactical Fighter Aircraft

RUSSELL R. BURTON, D.V.M., Ph.D.

Crew Technology Division, USAF School of Aerospace Medicine, Brooks Air Force Base, Texas 78235-5301

Tolerances (Physiology); Gravity; (Reprints).

BURTON RR. *A conceptual model for predicting pilot group G tolerance for tactical fighter aircraft.* Aviat. Space Environ. Med 1986; 57:733–44.

A static model based on eye-heart vertical distance has been developed which predicts group mean G tolerances relative to the application of any of the following anti-G methods and/or physiologic responses: a) anti-G suit, b) reclined seat, c) anti-G straining maneuver (AGSM), d) positive pressure breathing (PPB), e) gradual onset of G, f) isometric muscular contraction, and g) leg elevation. This model was validated with published data. A variation of this model (derived equation) predicts the amount of AGSM (in mm Hg) required, in combination with any of the anti-G methods/responses at any G level. This calculated effort of AGSM can be equated to level of fatigue and performance decrements. A level of 50 mm Hg or an increase of 2 G in the upright seat was the maximum AGSM recommended for routine use as an anti-G method for operational fighter pilots. Keywords:

FUTURE TACTICAL fighter aircraft will have maneuverability at least equivalent to, and probably better than, that of the F-16. With these high acceleration capabilities, G protection for pilots must be greater than that afforded by current operational systems. Certainly, the high number of G-induced loss of consciousness (GLC) episodes—with resulting loss of aircraft and pilot lives in our current tactical fighters—has identified the need for improved pilot protection against G (7).

Our present knowledge of G protection systems suggests that significant improvements in these systems may involve a reclined seat, positive pressure breathing (PPB), anti-G suits, and the anti-G straining maneuver (AGSM). The AGSM will be used throughout this text as a term covering all types of anti-G maneuvers; i.e., M-1, L-1, or any combinations of these specific techniques. The reclined seat and possibly the PPB systems will involve changes in engineering design concepts and in the aircraft frame. These design specifications must be decided early in the planning stages by engineers who, unfortunately, do not often have sufficient knowledge of or appreciation for human limitations in the G environment. Such design considerations for G protection become even more difficult when one realizes that a combination of these G protection systems and the methods will have to be used, because no single system or method will completely protect the pilot. Since combinations of these systems can cause complex physiologic interactions, the simple addition of each protective system/method may not accurately predict the complete G tolerance.

Consequently, a model has been developed which will predict G tolerances for a typical pilot or subject who is protected by any combination of these anti-G systems. This model is presented herein with theoretical considerations, validation data, and operational applications—including fatigue and performance. This static model is not intended to be used to determine dynamic types of G tolerances with temporal considerations.

Model Design

Physiologic/Physical Basis for Relaxed $+G_z$ Tolerance

Relaxed $+G_z$ tolerance to rapid G onset ($>0.5\ G\cdot s^{-1}$) is a direct function of eye-level arterial pressure, which is determined by heart-level arterial pressure. This eye-

This manuscript was received for review in July 1985. The revised manuscript was accepted for publication in September 1985.

Address reprint requests to Russell R. Burton, D.V.M., Ph.D., USAFSAM/VNB, Brooks AFB, TX 78235-5301.

TABLE I GROUP MEANS ± S.E.M. FOR 7 SUBJECTS AT 6 DIFFERENT SEAT BACK-HEAD ANGLES, WITH RELAXED ROR (100% PERIPHERAL LIGHT LOSS) G TOLERANCES. SUBJECTS WORE ANTI-G SUITS NOT INFLATED.

				SEAT BACK ANGLE					
				30°	65°	30°	65°	30°	65°
				HEAD ANGLE					
AGE	HT (cm)	WT (kg)	N[a]	12°	12°	25°	25°	45°	45°
				VERTICAL EYE TO AORTIC VALVE DISTANCE (cm)					
53 ± 3	178 ± 2	81 ± 5	7	33.4 ± 1.0	21.5 ± 0.8	34.3 ± 0.9	27.5 ± 0.6	33.2 ± 1.0	25.2 ± 0.9
				G TOLERANCE					
30 ± 3	___[b]	___[b]	7	3.9 ± 0.2	6.6 ± 0.3				
25 ± 2	178 ± 3	79 ± 4	9			3.7 ± 0.1	4.9 ± 0.1		
24 ± 1	182 ± 3	81 ± 3	9					4.0 ± 0.2	5.4 ± 0.3

[a] = number subjects per group
[b] Ht /wt not determined, but group was an "average" size

level arterial pressure is decreased by the hydrostatic pressure, defined by the following equation:

$$P_H = h\,d\,g \qquad \text{Eq. 1}$$

in which: P_H = hydrostatic pressure in mm Hg; h = height of the column (mm); g = ambient accelerative inertial force (G); and, d = fluid specific density relative to the specific density of Hg (13.6)—approximately 1/13.6 for blood. Changing the density of blood to that of mercury in this equation, and having the height of the column measured in millimeters, calculates a pressure in dimensions equivalent to arterial blood pressure (mm Hg). The relationship between these opposing forces (blood pressure and hydrostatic pressure) in relaxed man, during exposure to different G levels with different eye-heart vertical distances (h of Eq. 1), has been determined in a recent study by Burns and Whinnery (2). They accurately measured the eye to aortic valve vertical distance by using radiographic techniques in seven patients, seated in two different seat back angles (30° and 65°), for whom three different head angles were measured upright from the back (12°, 25°, and 45°). The result was six different eye-heart vertical distances, for each member of the group, ranging from 215 mm (65° seat with 12° head position) to 343 mm (30° seat with 25° head position). Using experimental subjects (groups of seven to nine) of similar group mean body size, these authors (2) determined the relaxed G tolerances (100% peripheral light loss) of every subject at each of six seat back-head angles (Table I). The subjects wore anti-G suits which were not inflated. The uninflated anti-G suit (operational model) gives the relaxed subject 0.3-G increased tolerance (6).

If the P_H of Eq. 1 can be directly related to the arterial systolic pressure (P_a) of man, then, as the h of this equation is reduced by reclining the body, G tolerance (g of Eq. 1) should increase, keeping P_H constant because P_a would remain constant. The application of Eq. 1 to these data of Table I for each group G-tolerance (100% peripheral light loss) determination (subjects relaxed wearing an uninflated anti-G suit) results in a product that is reasonably constant (range of 104.3 to 93.3) with a mean of 98.4 ± 1.54 S.E.M. (Table II). We can assume, therefore, by using Eq. 1, that a measurement of h will provide the P_a of a group of subjects.

Since these relaxed G-tolerance data (Table I), from which the mean P_a was derived, were determined by using light-loss criteria and not loss of consciousness, the P_a at zero means that arterial pressure at br⁻in level is still approximately 20 mm Hg—the intraocular pressure of man.

This P_a equates to the systemic arterial pressure at heart level (aortic valve) at 1 G, not including the intraocular pressure of 20 mm Hg. Adding 20 mm Hg to the P_H of 98.4 equates to a systemic systolic arterial pressure at heart level of approximately 120 mm Hg, a reasonable value for systolic arterial blood pressure. In using the P_a in calculating G tolerances, however, the intraocular pressure is not added (nor should it be) if

TABLE II. P_a (mm Hg) IS DERIVED FROM P_H AS DETERMINED USING EQUATION 1: $P_H = h \cdot G/13.6$.

Seat Back°	Head Angle°	P_a
30	12	95.8
65	12	104.3
30	25	93.3
65	25	99.1
30	45	97.6
65	45	100.1
	X ± S.E.M. =	98.4 ± 1.54

light-loss criteria are to be considered a valid operational end point (Eq. 2).

By using this P_a of 98.4 and rearranging Eq. 1, the G tolerance—G level of light loss—with various eye-heart vertical distances, can be predicted:

$$G = P_a \cdot d/h \qquad \text{Eq. 2}$$

in which: G = G tolerance; P_a = 98.4 (arterial blood pressure); d = 13.6; and, h = eye-heart vertical distance (mm).

A G-tolerance curve, developed using this G tolerance model (Eq. 2), is shown in Fig. 1.

Of particular importance in the development and use of this model is the fact that, although the physiologic arterial pressure remains constant, the increase in G tolerance, as the eye-heart vertical distance is reduced, is not constant. A reduction of approximately 25 mm Hg of P_a (Eq. 2) is equivalent to 1 G tolerance in the upright seat; but, in a 65° tilt-back seat with 12° head angle, 15 mm Hg is equivalent to 1 G tolerance. Similarly, acceleration protection methods which primarily affect the arterial blood pressure can also be considered, with h specified, when determining G tolerance effects.

Equation validation: Only three published studies have measured the eye-heart vertical distance and related it to G tolerance (2,3,14). Data from these 3 studies, compared with the G-tolerance curve calculated from Eq. 2, are shown in Fig. 1.

Some "standardization" of these data was necessary to allow comparisons. The G tolerance values of Crossley and Glaister (14), represented by the closed circles, were determined on subjects not wearing an uninflated anti-G suit; therefore, 0.3 G was added to their measured values. The eye-heart measurements of Burns (3) (open squares), were increased by 35 mm at the 13° and 30° seat back angles; for his eye-heart measurement was the distance from the eye to the aortic arch, and not the aortic valve—a vertical distance of approximately 35 mm. This measurement was not "standardized" for the other seat back angles of Burns (3), since the vertical distance "error" would be far less significant.

These additional data are in close agreement with the G tolerance curve of the model developed from Eq. 2, thereby supporting this approach as a predictor of relaxed rapid onset run (ROR) G tolerances over a wide range of vertical eye-heart distances for groups of subjects or pilots wearing uninflated anti-G suits.

G Increases from Anti-G Methods

Anti-G suit: The operational USAF anti-G suit, when inflated, gives the "relaxed" subject or pilot approximately 1-G extra tolerance. This 1-G increased tolerance appears to be independent of eye-heart vertical distance (13,14,18).

There are probably two reasons why the anti-G suit is not more effective at a reduced eye-heart vertical distance: a) The abdominal bladder of the anti-G suit confers approximately 80% of the increased tolerance from the entire G-suit—apparently by affecting the anatomic eye-heart distance and vascular resistance during G, which have less vertical components as the

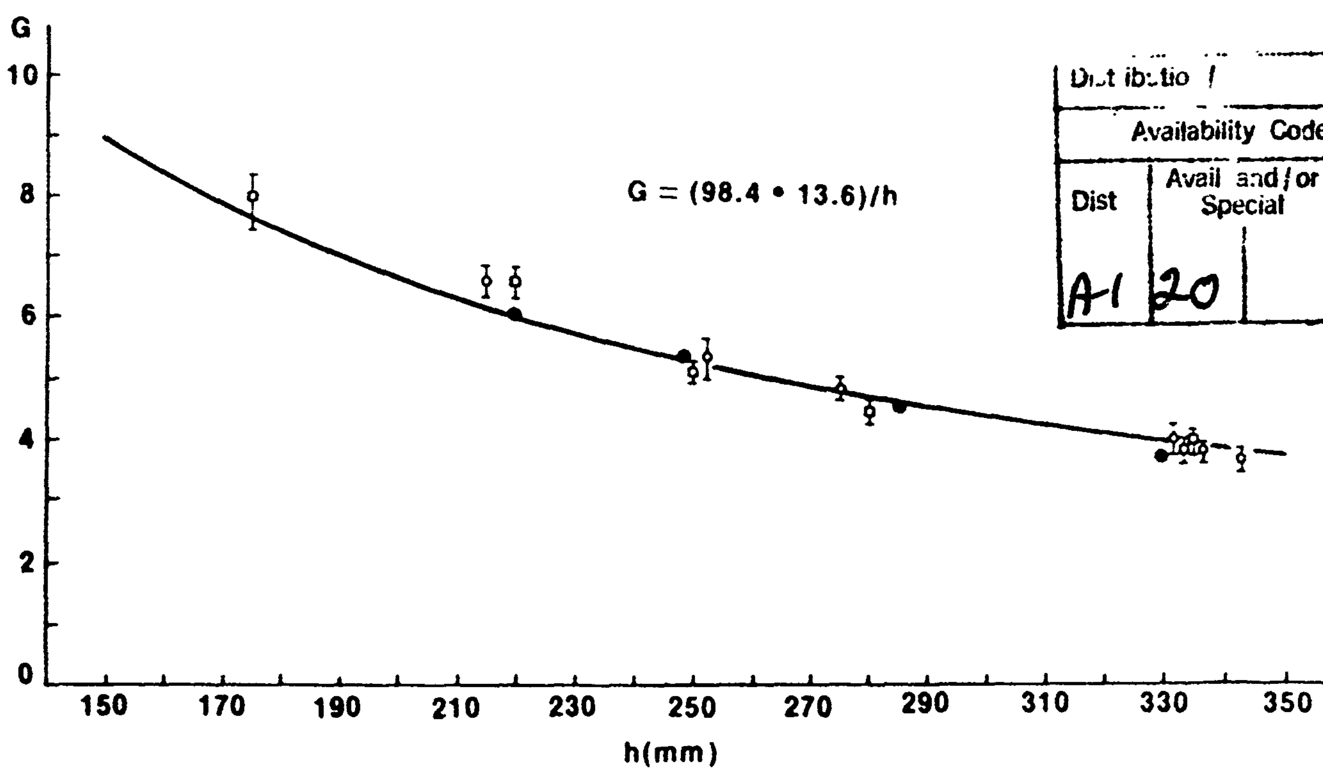

Fig. 1. G tolerances of relaxed subjects wearing an uninflated anti-G suit, as determined using Eq. 2 of text. Data represented by: open circles (○), (mean ± S.E.M.) are from Burns and Whinnery (2); open squares (□), from Burns (3); and closed circles (●), from Crossley and Glaister (14).

body is reclined (24,25,34,35); b) anti-G suit pressure is typically reduced as the seat back angle is increased (3,16,19,30). Reduced suit pressures are used because of subject comfort with only minor insignificant changes resulting in G tolerances.

Since the increase in G tolerance due to the inflated anti-G suit is approximately 1 G, at all seat-back angles (a wide range of eye-heart vertical distances), its effect on G tolerance is included as a simple additive value of 1 G to the result of the G tolerance model (Eq. 2). An implicit assumption here is that the anti-G valve used to inflate the suit acts fast enough for the suit to be effective as the G level is increasing.

Especially regarding GLC, an anti-G valve which inflates the anti-G suit significantly more rapidly than the present operational valve will confer upon a pilot or subject some additional G protection—but only for a brief period of time and early in the beginning of an aerial combat maneuver (ACM). Of course, this additional protection cannot be greater than the 1 G which the anti-G suit provides—it only provides this 1-G protection more rapidly, a factor which, of course, is critical.

Anti-G straining maneuver (AGSM): The greatest factor that contributes to G tolerance of pilots in the operational arena is the AGSM. The work of Wood's group in the 1940's (34,36), and the recent experience gained both in our laboratory (22) and while G-training TAC pilots on our centrifuge, all clearly show that for a group, 9 G—with the subject/pilot seated in an upright or 30° seat—is the realistic maximum tolerance in an operational aerial combat maneuvering environment where this G level must be routinely attained and, at times, sustained for several seconds.

We know that 9 G can only be tolerated in the upright seat by using the AGSM, and thus increasing G tolerance by some 4 G above the 5 G "relaxed" tolerance of a subject wearing an inflated anti-G suit. This AGSM must result in an increase of approximately 100 mm Hg of P_a, since P_a of Eq. 2 equals approximately 25 mm Hg for subjects in the upright seat—98.4 mm Hg with 4 G tolerance. The direct effect of intrapulmonary pressure on P_a, using the AGSM, was determined by Wood and Code (33).

The physiologic effectiveness of the AGSM is determined indirectly by measuring the esophageal pressure (P_{es}) which, under these conditions, is an accurate measure of the intrathoracic pressure. The relationships of P_{es} to P_a in the seated upright subject has been determined in animals (miniature swine) and in man. Burns *et al.* (4), at 3 different sustained G levels (+3, 5, and 7 G_z) in miniature swine, determined that th change in the P_{es} was directly and rectilinearly related to the resulting change in mean P_a at eye level with a proportionality constant of 0.86—1 mm Hg increase in P_{es} resulted in 0.86 mm Hg increase in P_a.

Burton *et al.* (9) measured both differential P_a and P_{es} in the same six subjects, who were using the anti-G suit and AGSM as required, at +1, 6, and 8 G_z sustained for a maximum of 60 s. The differential P_a was the difference between the minimum and maximum pressures measured during each G exposure. This differential systolic arterial pressure was found to be a direct function of the P_{es} pressure, although the P_a was usually higher than anticipated, especially during the 6-G exposure. This higher P_a can be accounted for by arterial vasoconstriction (gradual onset run, GOR, effect), since this study used sustained G (Table III).

Apparently, therefore, P_{es} can be used as an index of the effectiveness of the AGSM on the P_a of Eq. 2. In determining the effect of the AGSM (S) on G tolerance—since P_{es} is a pressure measured in mm Hg and has a direct effect on P_a—P_{es} is added to P_a in Eq. 2*:

$$G = (P_a + S) \cdot d/h \qquad \text{Eq. 3}$$

in which: S = AGSM or P_{es} (mm Hg), and other symbols are presented in Eq. 2.

Esophageal pressures alone were measured by Burns (3) in subjects at different seat back angles (h) during 8- and 10-G sustained exposures. On an individual basis, the maximum "average" P_{es} measured was 100 mm Hg

TABLE III. DIFFERENTIAL SYSTOLIC ARTERIAL BLOOD PRESSURE (ΔP_a) AND ESOPHAGEAL PRESSURES (P_{es}) FOR 6 SUBJECTS EXPOSED TO +1, 6, AND 8G_z SUSTAINED FOR A MAXIMUM OF 60 S. SHOWN ARE GROUP MEANS ± S.E.M. SUBJECTS WERE WEARING ANTI-G SUITS AS REQUIRED AND PERFORMING THE AGSM AND/OR 35 mm Hg OF PPB UNASSISTED (9).

G Level (Measured)	+1 G_z[c]	+6 G_z	+8 G_z
AGSM			
ΔP_a	65[a]	77	77
P_{es}	61.6 ± 3.5	48.5 ± 8.5	70.9 ± 5.1
G tol[b]	6.5	8.0	8.9
PPB			
ΔP_a	54[a]	58	68
P_{es}	33.2 ± 4.3	37.8 ± 5.2	58.4 ± 10.1
G tol[b]	5.3	7.5	8.4

[a] S.E.M. were not available.

[b] G tolerance calculated using Eq. 3, and adding 2 G for anti-G suit at 6 and 8 G and GOR effect, since exposure is sustained—see text under section title "G tolerances to high sustained G." 335 mm is used for h since subjects were seated in 13° seat

[c] The subject was asked to do an AGSM or use 35 mm Hg PPB at 1 G as a P_{es} control

*Although, in the pig, 1 mm Hg increase in P_{es} resulted in only 0.85 mm Hg increase in P_a, human data suggested a P_{es}:P_a relationship much more closely to one. Therefore, in this model and for simplicity, we have a 1 mm Hg increase in P_{es} result in a 1 mm Hg increase in P_a.

TABLE IV. ESOPHAGEAL PRESSURES (P_{es}) IN mm Hg IN GROUPS OF SUBJECTS (N) AS RELATED TO SEAT BACK ANGLES (HEAD ANGLE WAS ALWAYS 12°), h, AND CALCULATED (EQ. 3) AND MEASURED G TOLERANCES (3). IN CALCULATING THESE SUSTAINED G TOLERANCES FROM THE P_{es}, 2 G WAS ADDED FOR THE ANTI-G SUIT (1 G) AND THE GOR EFFECT (1 G).

Seat ∠	h (mm)	P_{es} (mm Hg)	N[a]	Calc G	Measured G
13°	334	52.9	3	8.2	8
30°	334	44.8	2	7.8	8
45°	280	40.7	3	8 8	8
55°	250	29.2	2	8 9	8
65°	220	15.3	3	9 0	8
75°	175	16.7	2	10.9	8
45°	280	76.5	2	10 5	10
65°	220	27 8	2	9.8	10

[a] Number of subjects per group.

in a subject exposed to 10 G in a 45° seat back with 12° head angle (h of 280 mm). These average P_{es}, on a group basis, are shown in Table IV as related to calculated (Eq. 3) and measured G tolerances with seat back angles and h.

Sustained G exposures, although shown here with measured P_{es} (Tables III and IV), require additional physiologic considerations in order to calculate the theoretical G tolerances obtainable under these circumstances. These considerations are addressed later in a section of "G Tolerance to High Sustained G."

Positive pressure breathing (PPB): Positive pressure breathing—both assisted by chest counterpressure** and unassisted—has been found to be a useful method for protecting subjects against G in the laboratory on the centrifuge and for protecting pilots in aircraft. The latter has only been done experimentally on a limited basis. PPB is assumed to increase intrathoracic pressure by the amount of PPB used. Studies have examined levels of PPB, unassisted, at 30 and 35 mm Hg (9,19,20,28); and assisted, at 30 to 70 mm Hg (5,26).

Methods of evaluating the effectiveness of PPB are similar to those used to measure the AGSM—principally esophageal pressure. The effect of PPB on P_a appears to be similar to that of the AGSM.

The P_{es} resulting from PPB has been measured only during sustained G exposures of +1, 6, and 8 G_z (Table III). These unassisted 35-mm Hg PPB centrifuge runs resulted in P_{es} at +1 and 6 G_z, similar to the level of PPB used in this study. At the +8 G_z level, however, P_{es} greater than the 35-mm Hg PPB used were recorded, thus indicating that an additional AGSM must have been used by the subject in order to augment the 35 mm Hg of intrathoracic pressure necessary to tolerate 8 G. As found for the AGSM portion of this study, P_a was higher than anticipated from the P_{es} as measured. As noted earlier in this text, some of the P_a is a function of vasoconstriction due to the sustained nature of these G exposures.

The Burns and Balldin study (5) found that a +9 G_z SACM was tolerated by subjects using an assisted 50- to 70-mm Hg PPB with an inflated anti-G suit. The authors reported that 50 mm Hg was more effective than the 70-mm Hg PPB, and was preferred by subjects. Although the EP was not measured in that study, more than 50 mm Hg would obviously be necessary to support the arterial blood pressure at a level required at +9 G_z. This adjunct intrathoracic pressure required from the AGSM can be calculated by using a modification of Eq. 3:

$$S = [(G \cdot h) - k]/13.6 \qquad \text{Eq. 4}$$

in which: S = same as Eq. 3; G = G tolerance − 1 G for G-suit; h = same as Eq. 2; and, k = constant of 1338, which is $P_a \cdot d$ of Eq. 2. Using Eq. 4, the additional P_a over the basic P_a of 98.4 mm Hg (Eq. 1) required at +9 G_z (upright seat) is 98.7 mm Hg. Since 50 mm Hg was developed by the assisted PPB, the subjects of the Burns and Balldin (5) study needed an additional 48.7 mm Hg which they produced with the AGSM.

G Tolerance to High Sustained G (HSG)

Unlike the operational ACM, which is a variable G environment, HSG maintains a constant G level (at least 6 G) for a minimum of 15 s (9). Two physiologic

**Assisted PPB in these studies used a chest counterpressure (inflated pressurized vest) equivalent to the level of PPB.

mechanisms are thus permitted to become operational and support G tolerance: a) arterial vasopressor effect found during the GOR type of G tolerance determination; and b) arm muscle isometric contraction (hand gripping), resulting in a reflex arterial pressure increase that occurs during the first 30 s to 1 min of muscular effort.

GOR effect: The arterial vasopressor effect during $+G_z$ exposures is well know, and occurs 6–8 s into an ROR G exposure (7,9,34). This response causes an increase in G tolerance of approximately 1 G, and is independent of seat back angles and G suit application (3,14,18). Consequently, during HSG tolerance calculations, this GOR (1-G) effect is added to the G tolerance determination (Eq. 2) for the anti-G suit benefit.

Isometric contraction effect: Isometric muscular contraction with hand gripping has been measured by Lohrbauer *et al.* (21), and by Quarry and Sodick (23). The Lohrbauer study found that a 50% maximum voluntary contraction resulted in an increase in P_a of approximately 20–24 mm Hg, and an increase in ROR and GOR tolerances of 1 G in subjects in an upright seat. This 1-G increase was also independent, and in addition to the 1 G for the anti-G suit.

Quarry and Spodick (23) reported similar arterial pressure increases from hand grip in both the sitting and supine individual, but did not measure G tolerance. Since the same level of pressure response occurred in the supine subject, however, this reflex must be considered in the model (Eq. 3) similar to the increase in P_a which results from the AGSM or from PPB. Effectiveness of a given pressure elevation, in terms of G tolerance, increases as h becomes smaller.

Nothing is known about the effect of these two cardiovascular reflex effects on ACM/GLC tolerances. We assume that, since the arterial pressure response is relatively slow as compared with the dynamic, ever-changing G environment of the ACM, these reflexes do not significantly affect the ACM tolerance. Consequently, they are not included in this model in determining ACM tolerances. However, in the HSG arena where the G level remains constant and where their effect has been measured on the centrifuge, both of these physiologic responses are important when considering duration of HSG tolerances (fatigue). That is to say, approximately 50 mm Hg less AGSM will be required to tolerate these high G levels, as G is sustained for a long duration.

In validating Eq. 2 and 3 with HSG tolerance data, these arterial pressure responses must be considered in calculating the "average" AGSM required to achieve HSG tolerances.

Leg Elevation Effect on G Tolerance

This model does not take into account changes in leg or heel line elevation in calculating G tolerances. Since elevating the legs does not affect the h of Eq. 2, then no effect would be expected in this model.

Burton *et al.* (12) reported no G benefit in "relaxed" GOR and ROR tolerances in elevating the heel line to 5 cm below the seat pan, as compared with heels on the floor of the centrifuge gondola with seat back angles of 23° and 28°. Voge (30) found that the position of the lower legs, whether vertical (on the floor) or elevated to 115° from the vertical, made no significant difference in relaxed G tolerances at 45° and 75° seat back angles.

These findings, suggesting no increased ROR tolerance with an expected improved venous blood return to the heart from raising the legs, are not surprising when the effects of the anti-G suit on G tolerance is once again considered. Since only 20% of the increase in ROR G tolerance is a function of G-suit leg pressure, improved venous return from the legs is only a minor physiologic mechanism in that regard (8).

On the other hand, the role of elevated legs in reducing fatigue during extended exposures to the G environment is unknown and could be an important factor, for the principal function of the leg support of the anti-G suit appears to be to reduce fatigue during ACM exposures (27).

Model Validation

The relaxed G-tolerance curve (Fig. 1) has already been validated in this article, and found to be an accurate measure of relaxed ROR G tolerance of groups of subjects wearing anti-G suits uninflated as a function of eye-heart vertical distance.

Standardization of Data

Using published data to validate this model for both ACM and HSG, G tolerances have required some standardization to allow comparisons. Standardization of seat back angles is particularly important since the head angle is particularly relevant in determining h of the model (Table II). Unfortunately, the angle of the head position is rarely described in these studies. Consequently, in order to use data from most studies in validating this model, seat back angles were standardized—converted to eye-heart distances—using the G-tolerance curve (Eq. 2 and Fig. 1).

Relaxed ROR G tolerances, determined at different seat back angles in various studies, were correlated to h (Fig. 1) by using the following equation:

$$h = k/G \qquad \text{Eq. 5}$$

in which: h = same as Eq. 2; k = same as Eq. 4; and G = relaxed ROR tolerance with G suit on but not inflated.

Since relaxed ROR tolerances are frequently determined without the G suit on the subject, 0.3 G was added to those tolerances to standardize those data to the G tolerance Eq. 2. In addition, other data were standardized for different light loss G tolerance criteria.

These calculations, determined for all of the G tolerance seat back angle studies published, are listed in Table V. Seat back angle is evidently not an accurate indicator of G protection nor of h. Although combining head position (angle) with seat back angle does add validity to the G protective capabilities of the seat dimensions, these data can still be misleading. In the study of Burns and Whinnery (2), a head position of 25° in both the 30° and 60° seat back angles produced

TABLE V. h IS CALCULATED (EQ. 5), EXCEPT WHERE NOTED FROM SEAT BACK ANGLE OR G TOLERANCE DATA FROM REFERENCED RESEARCH STUDIES.

Seat back (°)	Head (°)	h (mm)	Reference
75°	-	159	31
	12°	167[a]	3
	-	178	30
	-	191	13
	-	195	20
	30°	215	14
65°	12°	203[a]	3
	12°	215[a]	2
	OP[b]	245	11
	45°	252[a]	2
	OP	262	10
	25°	275[a]	2
60°	-	212	30, 31
	OP	260	19
	30°	270	14
	-	275	20
55°	12°	250[a]	3
	OP	260	11
45°	12°	280[a]	3
	-	284[a]	30
40°	OP	320	12
30°	OP	297	VNB Data Repository
	OP	305	11
	-	311	30
	-	330	18
	45°	332[a]	2
	OP	334	10
	12°	334[a]	2
	12°	343[a]	3
	25°	343[a]	2

[a] h is measured.

[b] OP = operational position (near vertical)

a greater h than for the more erect head angle of 45°. For instance, this apparent anomaly resulted from "head angle" articulations relative to the 60° seat back, as follows: 12° head angle allowed back support of 26 in.; 25° head angle had back support of only 14.8 in.; but, with 45° head angle, 21.5 in. of back support was available.

Obviously, "seat back angle" descriptions must be detailed in order to predict G tolerances. Of course, this difficulty is circumvented by using only the eye-heart vertical distance in predicting G tolerances from various body positions.

Relaxed G Tolerances

"Relaxed" G tolerances can include PPB, GOR, and anti-G suit inflation type of support at different seat back angles. Various combinations of these relaxed tolerances have been determined experimentally, and are compared with G tolerance values calculated using the model (Table VI). For these G tolerance calculations, h was indirectly determined, using Eq. 5. The G used in Eq. 5 for these determinations was the ROR relaxed-G values of subjects, wearing uninflated anti-G suits, as measured in the referenced study. The calculated G-tolerance values, using Eq. 3, are similar to those determined on the centrifuge and reported as group means by those referenced. The mean difference between calculated and measured G tolerance for 17 groups from 6 studies is 0.2 G per group.

Straining G Tolerances

The G tolerance of an individual can be increased significantly by performing the AGSM alone or in combination with PPB. The most precise physiological evaluation of this straining effort, to determine the effectiveness of its anti-G capability and validate the model, would require that the intrathoracic pressure or P_{es} be measured during high-G ACM or HSG exposures. Unfortunately, these data are not readily available for the ACM. The P_{es} was measured in eight subjects during an 8-G ACM experiment in our laboratory (12). These data were only reported as an average value over the entire ACM exposure in order to compare with HSG exposures of the same study. However, P_{es} values were measured (but unpublished) during two 8-G peaks during the SACM for the eight subjects. These data (mean ± S.E.) for each of three seat back angles, 40°, 28°, 23°, respectively, follow: a) P_{es} (in mm Hg) first 8-G peak, 112 ± 9.0; 107 ± 8.6; 111 ± 9.9; and b) second 8-G peak, 108 ± 12.2; 96 ± 5.9; 103 ± 11.0. Shown in a figure from this same study is an analog strip-chart of one subject during a single 8-G ACM exposure with a P_{es} of approximately 120 mm Hg when the subject was at each 8-G peak. Using these approximately 100-mm Hg values from this study and calculating the G tolerance expected (Eq. 3), the subject should have tolerated approximately 9 G—a deduction which implies that he overstrained for the ACM. Excessive AGSM pressures are to be expected when subjects/pilots are exposed to high G for short durations.

Considerable P_{es} data are available for HSG exposures with and without PPB. These data, as related to G tolerance measured on the centrifuge and calculated using Eq. 3, were discussed earlier in this article and are shown in Tables III and IV. An important finding to reiterate here is that, in calculating HSG tolerances using Eq. 3, 2 G must be added to the calculated G value for the anti-G suit (1 G) and the GOR effect (1 G). If the pilot or subject is also contracting (tensing) his arm musculature (hand gripping) during HSC exposures of 30 s or more, then 25 mm Hg P_a should be added to the pressure component of Eq. 3 in calculating G tolerances.

As shown in Tables III and IV, the G tolerances calculated for HSG in the upright seat, with and without PPB, and at various seat back angles with only AGSM, are similar to the group mean measured G tolerances. Particularly important is the observation that, in all of these group comparisons (except for two instances found in Table IV), the estimated G tolerance is greater than the G level actually reported. In those two cases where the estimated G was less than the measured G, the difference was only 0.2 G. These comparisons of

TABLE VI. COMPARISONS OF CALCULATED (USING EQ. 3) AND DETERMINED (IN A CENTRIFUGE) G TOLERANCES AT DIFFERENT SEAT BACK ANGLES AS REPORTED IN THE REFERENCES h WAS DETERMINED INDIRECTLY, USING EQ. 5 AND RELAXED UNPROTECTED ROR G TOLERANCES REPORTED IN THE SAME STUDIES. ANTI-G METHODS/SYSTEMS WERE USED AS INDICATED

					G Tolerance			
Seat Angle	h[a]	GOR	G-Suit	PPB	Measured	Calculated[b]	ΔG[c]	References
75°	215	yes	yes	no	8.4	8.2	−0.2	14
60°	270	yes	yes	no	7.0	7.0	0	
20°	330	yes	yes	no	6.0	6.1	0.1	
40°	320	yes	no	no	4.9	5.2	0.3	12
		no	yes	no	5.5	5.2	−0.3	
28°	350	yes	yes	no	4.3	4.8	0.5	
		no	yes	no	5.0	4.8	−0.2	
23°	360	yes	yes	no	4.5	4.7	0.2	
		no	yes	no	5.2	4.7	−0.5	
75°	191	no	yes	no	7.6	8.0	0.4	13
15°	340	no	yes	no	4.3	4.9	0.6	
60°	260	no	yes	no	6.5	6.1	−0.4	19
		no	no	yes	5.5	6.5	1.0	
		no	yes	yes	7.4	8.0	0.6	
75°	159	yes	no	no	9.7	9.4	−0.3	31
60°	212	yes	no	no	7.3	7.3	0	
15°	340	yes	yes	yes	6.6	7.2	0.6	26
							$\Delta G^{d} = +0.2$	

[a] h was determined using Eq. 5.

[b] G tolerance calculated using Eq. 3.

[c] ΔG = calculated G − measured G.

[d] $\Sigma\Delta G$/n of groups = ΔG.

calculated and measured G tolerances show agreement, particularly when it is assumed that most subjects (and pilots, as well) will usually maintain some margin of safety by doing a more vigorous AGSM than the minimum necessary to tolerate the HSG environment.

AGSM Effects of Fatigue and Performance

The AGSM required at any G level can be calculated using Eq. 4. This information is useful in relating the AGSM, required for G tolerance, to fatigue development during the ACM and performance during G exposures.

Fatigue

G tolerance in the ACM arena is, to a large measure, determined by fatigue of the pilot, who is eventually unable to continue with the G maneuvers because the energy used to maintain an adequate AGSM finally exhausts the pilot.

ACM tolerances, as a function of duration of exposure to a continuous 4.5 to 7.0 G profile which was repeated until the subject became too fatigued to continue, were determined on our centrifuge. The subjects wore inflated anti-G suits and were seated in one of 4 different seat-back angle configurations for each ACM tolerance determination: 13° (h = 340 mm); 30° (h = 325 mm); 55° (h = 260 mm); and, 65° (h = 245 mm). As the seat back angle increased (h became smaller), the AGSM required to maintain vision was reduced as calculated using Eq. 4: a) an h of 245 mm (65° seat) required 10 mm Hg AGSM; b) an h of 260 mm required 16 mm Hg AGSM; c) an h of 305 mm required 36 mm Hg AGSM; and, d) an h of 340 mm required 52 mm Hg AGSM. An h of 223 mm theoretically would require no AGSM—the subject could tolerate the 7-G ACM "relaxed." Extrapolation of the time tolerance data (11) which is exponential, to this h of 223 mm indicates that a 4.5/7-G ACM could be tolerated for 650 s.

On the other hand, a 9-G ACM profile with the subject seated in an upright seat (h = 340) required an AGSM of 102 mm Hg—considered to be the maximum capability for a group of subjects or pilots. This ACM profile was tolerated for 74 s by a group of seven subjects in the Burns and Balldin study (5).

By using these data, the percentage reduction in ACM tolerance time can be calculated and related to the amount (mm Hg) of AGSM required to tolerate these G exposures. Percentage reduction in ACM was calculated as follows:

$$R = [(650 - T)/650] \times 100 \qquad \text{Eq. 6}$$

in which: R = Reduction in ACM (%); and T = ACM tolerance (s).

The relationship between the percentage reduction in ACM tolerance time (Eq. 6) is related to the AGSM (mm Hg) required in Fig. 2. Of course, the AGSM required to tolerate these G levels (as calculated in Eq. 4) is expected to be less than actually used by individuals, since overstraining routinely occurs. This overstraining does not occur during the 9-G ACM, however, since the maximum capability of most subjects is required as the minimum effort. Because of these considerations, the operational fatigue curve is probably more linear (less hyperbolic) than shown in Fig. 2. Nonetheless, the AGSM is correlated with level of fatigue during the ACM. Clearly, fatigue is an important consideration in choosing the AGSM as an anti-G protective method of repeated ACMs, and should be used only in moderation—probably no higher than 50 mm Hg.

In the 9-G ACM study in which 50-mm Hg-assisted PPB was used (5), the PPB appeared to be useful in reducing fatigue by the amount of AGSM that PPB replaced in the development of the adjunct arterial pressure needed to tolerate 9 G. The percentage ACM reduction with the PPB dropped from 89% to 76%—an improvement of 15% (Fig. 2).

Supporting the legs during the ACM, either through improved leg coverage of the anti-G suit or by elevating the heel line, appeared to reduce the rate of fatigue development. The study of Shaffstall and Burton (27) clearly demonstrated the role of the anti-G suit in increasing tolerance to the ACM. One would assume that elevating the legs would have a similar beneficial effect, however, this study is yet to be accomplished.

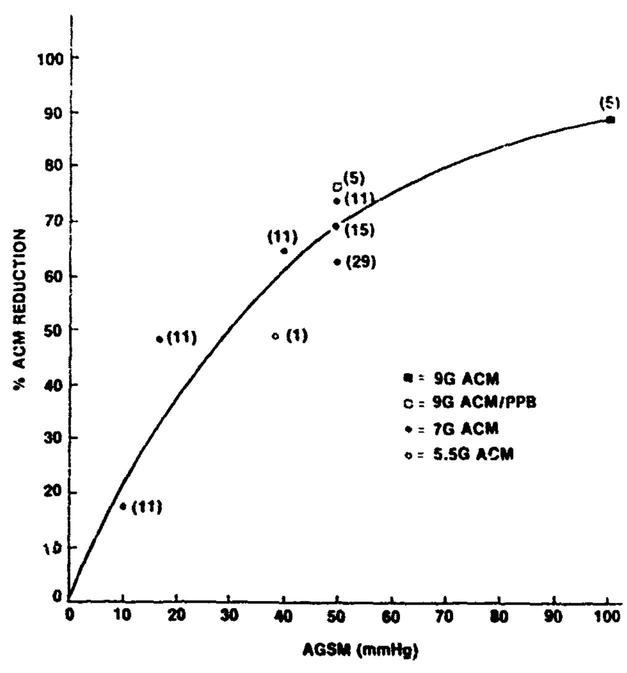

Fig. 2. The percentage reduction in ACM tolerance time is compared to the amount of AGSM required to tolerate the G levels of the ACM. References to the studies from which the data were obtained are in parentheses.

Performance

In considering G tolerances and the effectiveness of anti-G protective methods, subject or pilot performance is an extremely important operational criterion. Unfortunately, performance measurements during G exposures have been limited to: tracking (error score), target (hit/miss score), visual field size, and "complex choice reaction time." The reason for this limited range of performance tests is that the duration of time at G is not long, and most performance tasks require considerable time to accomplish.

Perhaps the principal (most basic) performance quantifier is that of visual field size. If the pilot is unable to see (loss of peripheral and central vision), then performance will be poor. Gillingham and McNaughton (17) reported, in relaxed subjects without G suits during GOR exposures: complete visual loss near 5 G in the upright seat; similar light loss at 6 G in the 45° seat; and some peripheral vision remaining at 7 G in the 65° seat. Of course, with the AGSM and with the subjects wearing anti-G suits, visual fields with considerable peripheral vision can be maintained at 7 G, even in the upright seat.

At HSG exposures with subjects performing the AGSM, reductions in target-tracking task performance (percentage) were found to be exponentially related to the G level. Severe reductions in performance (above 50%) were found at 7 G, with subjects in the upright seat wearing an inflated anti-G suit (9). An important factor, however, is that these subjects probably were not proficient at performing the AGSM; for 7 G appeared to be their maximum capability in an upright seat. This maximum capability in performing an effective AGSM is extremely important in measuring performance at G, and varies remarkably within a subject population and among laboratories. Certainly, a group of subjects whose maximum G capability in an upright seat with an anti-G suit and performing an AGSM is only 6.35 ± 0.55 (X ± S.D.), such as reported by Cohen (13), would not perform well at 6 G while they were straining maximally. On the other hand, since 6.4 G in an upright seat requires only a 37-mm Hg AGSM—which is only 37% of the maximum capability of 100 mm Hg AGSM possible for a well G-trained centrifuge rider or pilot—any decrease in performance due to G would be expected to be considerably smaller. In another study which considered both a tracking task and a choice reaction time task, increased seat back angles improved performance scores only as maximum G tolerances were approached in the more upright seats (20).

This assumption, that performance is only compromised significantly at the threshold of maximum G capability, is borne out with data from 3 ACM studies in which well trained, high-G subjects were used (10,11,12). In a tracking task with subjects and pilots performing an 8-G, 95-s duration ACM, error scores were not affected by seat back angles of 23°, 28°, or 40° (11). Repeated 10-, 8-, 6-G ACMs of 122-s duration, with subjects using a 65° seat, found that error rate scores (errors/s of G exposure) were not statistically different at each of these G levels (10). In this final study, both tracking error scores and accuracy

(hits/misses) performance criteria were not different for a 7-G ACM (until subject fatigue) at any of the 4 seat back angles of 13°, 30°, 55°, and 65° (12). However, since the subjects were able to perform for *longer* durations at the greater seat back angles, total hits were, of course, increased. In these studies, wide ranges in the required AGSM were used without significant differences in performance being found.

The conclusion, therefore, is that performance during the ACM will not be enhanced by reclining the pilot at G levels any pilot can effectively tolerate in the upright seat. This model defines that limit as 9 G for a group of pilots. Certainly, specific pilots will not tolerate 9 G well, as opposed to others who can perform effectively above this G level. Furthermore, if multiple peaks to 9 G are required, or if the pilot is fatigued already when the 9-G ACM is required, then performance can be expected to improve as the seat is reclined or PPB is applied. Also, since the pilot will be able to tolerate the ACM for *longer* durations in reclined seats, the total "kills" will be increased significantly over those of the pilot flying the conventional upright seat. This observation was made by Burton and Shaffstall (11) who found a 274% increase in hits when using a 65° seat as compared with the 13° seat, when the increased sustainability at G was allowed to influence the results.

Discussion

Historically, the anti-G suit was developed as an emergency, stop-gap method for improving G tolerance for World War II vintage fighter planes. This suit was not intended by its developer (34) to be the permanent solution to the high-G problem. They recognized the limitations of the anti-blackout suit back in 1946, when they noted that these suits "...are not the answer to the (blackout) problem...," and "...anti-blackout suits soon will be as obsolete as the planes in which they were used..." True, the planes became obsolete, but, unfortunately, the anti-G suit, with only minor modifications, remains today as the foundation for anti-G protection for all advanced fighter aircraft developed over the last four decades.

The anti-G benefits of the reclining seat have been known since the early work of Buehrlen, in 1937, which resulted in three prototype reclining seats being tested in aircraft by the Germans in World War II (32). Yet, probably because of engineering problems inherent in reclining seat design, this concept in protecting pilots against G was not developed for operational use by any nation. Also, since the anti-G suit and AGSM were "effective," inexpensive, and without aircraft frame design constraints, the requirement for the reclined seat was nonexistent. The Germans probably pursued the development of the reclining seat more than did the allied nations during World War II because Germany did not have anti-G suits (34).

Of course, unlimited possibilities exist in seat back angles and in combination with different head angles. This range is evident in the different eye-heart distances, "h" (Table V), which occur at the same seat back angles. Consequently, this model uses the eye-heart vertical distance (h of Eq. 2) to determine the effect of changing body position on G tolerance. To validate this model, much of the published data had to be "standardized" to an eye-heart distance, which was determined indirectly using Eq. 5 (Fig. 1). This approach is not without some hazard and valid criticism; for, obviously, these published data are essentially "fitted" to the G-tolerance curve (Fig. 1) which are recalculated with these "standardized" data to prove that the basic assumptions of this model are valid. However, emphasis must be placed on the fact that some direct eye-heart data are available, and that these compared favorably with the G-tolerance curve of Fig. 1, as developed from Eq. 2. Of course, data specifically developed to validate this model will have to be developed in the laboratory on the centrifuge as rapidly as possibly.

Specific areas of model validation which should be addressed include various PPB and h combinations, as related to G tolerances as well as G tolerances and G protection above 9 G, where little research has been conducted. Of particular interest is the ability of a subject to perform a 100-mm Hg AGSM with the seat pan angle necessary for a reclined seat of 55° or greater. If this level of AGSM is possible at an h of 260 mm, then a tolerance level of 11.8 G is predicted possible. In addition the effect of various combinations of head-body seated positions on h, as related to line of sight inside the cockpit and to visual fields outside the cockpit, would be appropriate for study.

Our present understanding of G tolerance enhancement by reclining the seat back suggests that, as visual light-loss criteria are less affected by G, uncomfortable pressures on the chest wall becomes a significant factor in tolerating G. Some of this difficulty will no doubt be reduced with PPB and chest counterpressure. However, suggesting that G tolerance in a 75° seat with maximum AGSM and or PPB would be greater than 15 G (as indicated in Fig. 3) is difficult to imagine, and is probably unrealistic.

The AGSM, a major component in the current operational anti-G system, has all of the attributes of the "perfect" personal protective system—available, cheap, unencumbering, light weight, and independent of the aircraft frame. But, it is hard work. Therefore, we should determine the acceptable level of AGSM to be used in an "advanced" anti-G system. After this level is established, then various combinations of anti-G methods and systems can be considered in some detail. Of course, the best anti-G system would afford total G protection without requiring any AGSM. At 9 G, with a subject wearing an inflated anti-G suit, an h of 167 would be required. This h can only be obtained with a 75° seat back angle and the head at 12°, a position which is probably not operationally practical. It is not reasonable to recline a pilot to an angle greater than 75° because of angle-of-attack considerations.

Therefore, some additional form of anti-G system must be considered, and this is now limited to the AGSM or PPB (assisted or unassisted). The recent work of Burns and Balldin (5) suggests that about 50-mm Hg-assisted PPB is the maximum which appears to be useful in increasing G tolerance—70 mm Hg resulted

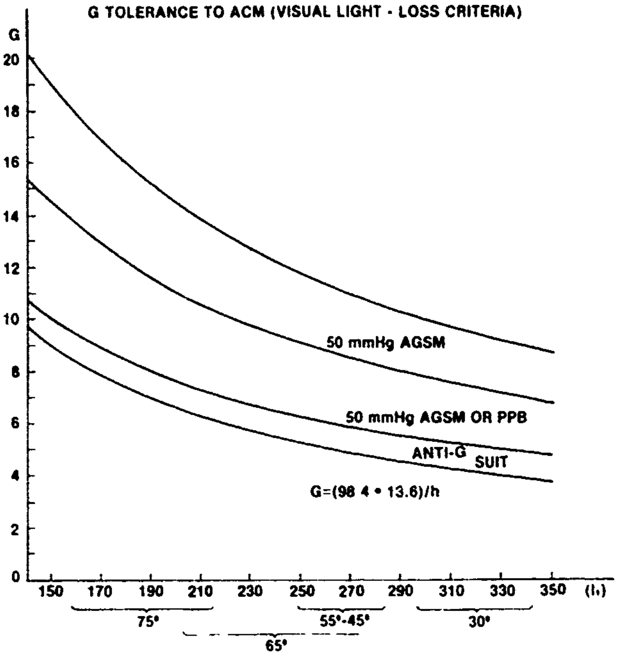

Fig. 3. G tolerances are shown for the ACM determined for various eye-heart vertical distance (h) in mm and seat-back angles, with subjects or pilots using different anti-G protective methods and systems.

in less G tolerance than 50 mm Hg. Similarly, 50 mm Hg of AGSM appears to be a comfortable level for repeated routine use by a pilot performing ACM. If 50 mm Hg of AGSM or PPB is considered to be a reasonable level to be used routinely in an operational anti-G system, then the current U.S. Air Force and U.S. Navy operational tactical fighter aircraft are now providing only 7-G protection systems while flying 9-G aircraft. Also, the proposed tactical life support system (TLSS), using assisted 50-mm Hg PPB and un upright seat, must be considered a 7-G system by these criteria: for 9 G can only be "tolerated" by using an additional 50 mm Hg of AGSM.

Some question persists regarding the possibility of developing more than 100 mm Hg of intrathoracic pressure—50 mm Hg of PPB with an additional 100 mm Hg from the AGSM. Developing 150 mm Hg of intrathoracic pressure could result in an increase of 6 G in the upright seat. Although 50 mm Hg of additional intrathoracic pressure was determined to be needed (in addition to the 50 mm Hg of assisted PPB) to tolerate 9 G in the upright seat, the belief is that, for a sustained intrathoracic pressure increase such as required with an AGSM, a total of 100 mm Hg is the maximum pressure possible (for a group mean value) that can be developed within the thorax by the diaphragm.

Considerable confusion has existed over the capabilities of the reclining seat as an anti-G system: a) will it improve pilot performance over the upright seat, and b) will it eliminate G as a limiting factor in high performance aircraft? This review and model indicate that reclined seats will do neither. Performance, as measured per unit time at G, will only be improved as the pilot nears his G capacity which, in the upright seat, is probably 9 G. During sustained or repeated high G maneuvers, however, the duration of tolerance of the pilot will be extended, thus providing an improved total performance score. Since a head position with a high angle is critical for pilot performance but increases h in the reclined seat back, practical reclined seats will only be able to increase G tolerance by approximately 2 G, but that 2 G will reduce the requirement of the AGSM by one half for a 9-G system. In other words, with 50 mm Hg of assisted PPB, no AGSM will be required at 9 G; or, if PPB is not used, only 50 mm Hg of AGSM will be necessary. Pilot endurance at 9 G or in repeated ACMs will thus be significantly increased.

In this article, the level of 50-mm Hg intrathoracic pressure has been suggested as the maximum level that should be required of a pilot straining in routine operations. This adjunct pressure of 50 mm Hg maximum is suggested for three important reasons. a) It is a level that already causes significant fatigue (70%, in an ACM environment: Fig. 2). With greater levels of AGSM, fatigue increases to the point that severely limits ACM scenarios. b) At higher levels, some significant compromise of performance must be expected. This performance detriment is probably not a critical consideration in current aircraft, since maintenance of the aircraft maneuver is the only performance required at extremely high G. If, however, in future aircraft, as anticipated, more sophisticated performance will be required, the 50-mm Hg level becomes more critical. c) G-induced loss of consciousness accidents may be expected to continue to occur, if near maximum straining is required to maintain vision for the average pilot at the performance maximum of the aircraft. A 50% effort is a more realistic requirement to impose, given day-to-day variations in individual straining G tolerances.

In conclusion, therefore, a 55° to 60° seat back angle can be expected to permit a G-protection system that is more consistent with the 9-G environment where current operational aircraft occasionally fly, and where future aircraft will probably routinely perform.

REFERENCES

1. Balldin UI, Myhre K, Tesch PA, Wilhelmsen U, Andersen HT. Isometric abdominal muscle training and G tolerance Aviat. Space Environ. Med. 1985; 56:120–4.
2. Burns JW, Whinnery JE. Significance of headrest geometry in +Gz protective seats. Aviat. Space Environ. Med. 1984; 55:122–7.
3. Burns JW. Re-evaluation of a tilt-back seat as a means of increasing acceleration tolerance. Aviat Space Environ. Med. 1975; 46:55–63.
4. Burns JW, Parnell MJ, Burton RR. Venous return during +Gz stress in miniature swine (MS). Fed. Proc. 1984, 43:907.
5. Burns JW, Balldin UI +Gz protection with assisted positive-pressure breathing (PPB). In: Preprints of the Aerospace Medical Association Annual Scientific Meeting. Washington, DC: Aerospace Medical Assoc., 1983:36–7.
6. Burton RR, Parkhurst MJ, Leverett SD Jr. +Gz protection afforded by standard and preacceleration inflations of the bladder and capstan type G-suits. Aerospace Med. 1973; 44:488–94.
7. Burton RR, Whinnery JE. Operational G-induced loss of

consciousness. something old; something new. Aviat. Space Environ. Med. 1985, 56:812–7.
8. Burton RR, Krutz RW. G-tolerance and protection associated with anti-G suit concepts. Aviat Space Environ. Med 1975; 46:119–24.
9 Burton RR, Leverett SD Jr, Michaelson ED Man at high sustained +Gz acceleration: a review. Aerospace Med. 1974; 45:1115–36.
10. Burton RR. Human responses to repeated high G simulated aerial combat maneuvers. Aviat. Space Environ. Med. 1980; 51:1185–92.
11. Burton RR, Shaffstall RM. Human tolerance to aerial combat maneuvers. Aviat. Space Environ. Med. 1980; 51:641–8.
12. Burton RR, Iampietro PF, Leverett SD Jr. Physiologic effects of seatback angles <45° (from the vertical) relative to G Aviat. Space Environ. Med. 1975; 46:887–97.
13. Cohen MM. Combining techniques to enhance protection against high sustained accelerative forces. Aviat. Space Environ. Med. 1983; 54:338–42.
14. Crossley RJ, Glaister DH Effect of posture on tolerance to positive (+Gz) acceleration In: Adaptation and acclimatization in aerospace medicine. AGARD No. 82. 1971; 6-1 to 6.
15. Epperson WL, Burton RR, Bernauer EM. The influence of differential physical conditioning regimens on simulated aerial combat maneuvering tolerance. Aviat. Space Environ Med. 1982; 53:1091–7.
16. Frazier JW, Whitney RU, Ashare AB, Rogers DB, Skowronski VD. G suit filling pressure determined by seat back angle. Aerospace Med. 1974. 45:755–7.
17. Gillingham KK, McNaughton GB. Visual field contraction during G stress at 13°, 45°, and 65° seat back angles. Aviat. Space Environ. Med. 1977; 48:91–6.
18. Glaister DH. The influence of seat back angle on acceleration tolerance. Flying Personnel Research Committee (1365) London: RAFIAM, Ministry of Defense, 1978:6–9.
19. Glaister DH, Lisher BJ. Centrifuge assessment of a reclining seat. AGARD-CP189. 1976; A4-1 to 8
20 Glaister DH, Lisher BJ. The effect of acceleration and seat back angle on psychomotor performance. In: Preprints of the Aerospace Medical Association Annual Scientific Meeting. Washington, DC: Aerospace Medical Association, 1978:58–9.
21. Lohrbauer LA, Wiley RL, Shubrooks SJ, McCally MN Effect of sustained muscular contraction on tolerance to +Gz acceleration. J. Appl. Physiol. 1972; 32:203–9.
22. Parkhurst MJ, Leverett SD Jr, Shubrooks SJ Jr. Human tolerance to high, sustained +Gz acceleration Aerospace Med. 1972; 43:708–12.
23. Quarry VM, Spodick DH. Cardiac response to isometric exercise—comparative effects with different postures and levels of exertion. Circulation, 1974; 49:905–20.
24. Rushmer RF A roentgenographic study of the effect of a pneumatic anti-blackout suit on the hydrostatic columns in man exposed to positive radial acceleration. Am. J. Physiol. 1947; 151.459–68.
25 Rushmer RF. The effect of positive radial acceleration on the intrarectal pressure. J. Aviat. Med. 1947; 18:96–101.
26. Shaffstall RM, Burton RR Evaluation of assisted positive-pressure breathing on +Gz tolerance. Aviat. Space Environ. Med 1979; 50:820-4.
27. Shaffstall RM, Burton RR. Evaluation of a uniform pressure anti-G suit concept. In: Preprints of the Aerospace Medical Association Annual Scientific Meeting. Washington, DC Aerospace Medical Association, 1980:96–7
28. Shubrooks SJ Positive-pressure breathing as a protective technique during +Gz acceleration J. Appl. Physiol. 1973; 35:294–8.
29. Tesch PA, Hjort H, Balldin UI. Effects of strength training on G tolerance. Aviat. Space Environ. Med. 1983; 54:691–5
30. Voge VM. Psycho-physiological assessment of acceleration-induced changes in various seat configurations Aviat. Space Environ. Med 1977; 48:527–38.
31 Voge VM. Comparison of several G-tolerance measuring methods at various seatback angles. Aviat. Space Environ. Med. 1978; 49:377–83.
32. Von Beckh HJ Positioning of aircrews—ultima ratio of G protection? Aerospace Med 1972; 43:743–54.
33. Wood EH, Code CF. The physiologic basis of voluntary (self-protective) maneuvers capable of increasing man's tolerance to positive acceleration. 17th International Physiology Congress, 1947:311–2
34. Wood EH, Lambert EH, Baldes EJ, Code CF. Effects of acceleration in relation to aviation. Fed. Proc 1946; 5:327–44
35. Wood EH, Clark DM, Lambert EH. An analysis of factors involved in the protection afforded man by pneumatic anti-blackout suits. Fed. Proc. 1945; 4:79.
36. Wood EH, Hallenbeck GA. Voluntary (self protective) maneuvers which can be used to increase man's tolerance to positive acceleration. Fed Proc. 1945, 4:78–9.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

A178 431

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAFSAM-TR-85-55	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAF School of Aerospace Medicine 6b. OFFICE SYMBOL (If applicable) USAFSAM/VNB	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Human Systems Division (AFSC) Brooks Air Force Base TX 78235-5301	7b ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION USAF School of Aerospace Medicine 8b. OFFICE SYMBOL (If applicable) USAFSAM/VNB	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Human Systems Division (AFSC) Brooks Air Force Base TX 78235-5301	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 62202F PROJECT NO. 7930 TASK NO. 14 WORK UNIT ACCESSION NO. 45

11. TITLE (Include Security Classification)
A Conceptual Model for Predicting Pilot Group G Tolerance for Tactical Fighter Aircraft

12. PERSONAL AUTHOR(S)
Burton, Russell R.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 1 Jan 85 TO 15 Apr 85	1985 May 1	12

16. SUPPLEMENTARY NOTATION
This is a reprint of a periodical appearing in Aviation, Space, and Evironmental Medicine, 57(8):733-744 (August 1986).

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	G Tolerances, Acceleration, Mathematical Models, Anti-G Straining Maneuver, Pilots Stress (Physiology) Fighter Aircraft Pilots.
06	11		
01	02		

19 ABSTRACT (Continue on reverse if necessary and identify by block number)
A static model based on eye-heart vertical distance has been developed which predicts group mean G tolerances relative to the application of any of the following anti-G methods and/or physiologic responses: a) anti-G suit, b) reclined seat, c) anti-G straining maneuver (AGSM), d) positive pressure breathing (PPB), e) gradual onset of G, f) isometric muscular contraction, and g) leg elevation. This model was validated with published data. A variation of this model (derived equation) predicts the amount of AGSM (in mm Hg) required, in combination with any of the anti-G methods/responses at any G level. This calculated effort of AGSM can be equated to level of fatigue and performance decrements. A level of 50 mm Hg or an increase of 2 G in the upright seat was the maximum AGSM recommended for routine use as an anti-G method for operational fighter pilots.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Russell R. Burton	22b. TELEPHONE (Include Area Code) (512) 536-3521 22c. OFFICE SYMBOL USAFSAM/VNB

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED